

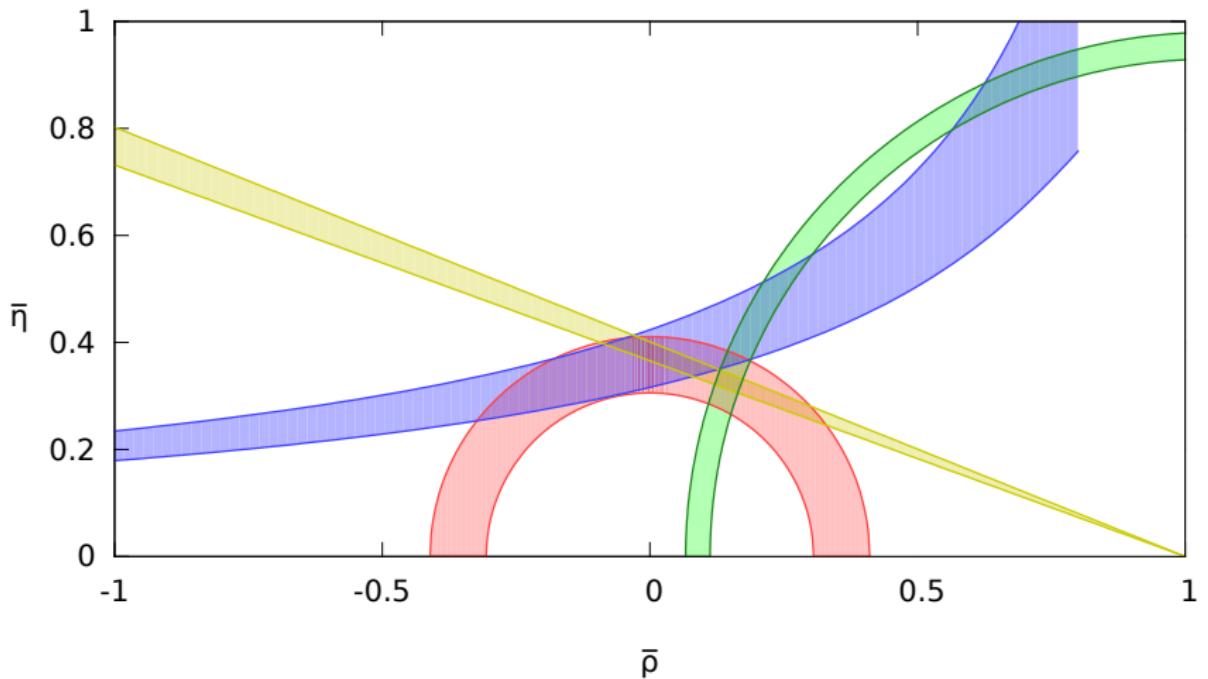
B physics with non-perturbatively tuned relativistic heavy quarks

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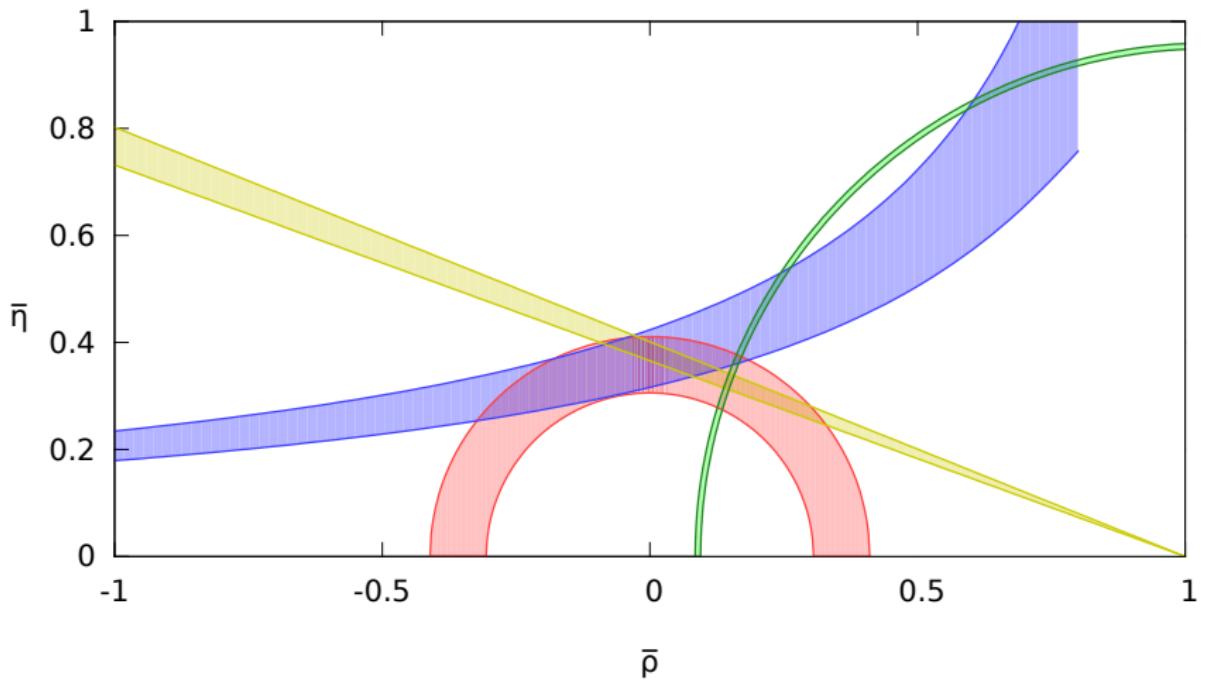
QCD on a Lattice at Zero Temperature

Mike Creutz	New lattice fermions, Quark masses and strong CP, . . .	BNL
Tomomi Ishikawa	B physics, QCD + QED, $(g - 2)_\mu$, . . .	RBRC
Taku Izubuchi	QCD + QED, $(g - 2)_\mu$, CAA, . . .	BNL / RBRC
Chulwoo Jung	Nucleon mass and strange content, Kaon physics, . . .	BNL
Taichi Kawanai	B physics, Heavy quarkonium potential, . . .	BNL / RIKEN
Christopher Kelly	Kaon physics, Light hadronic quantities, . . .	RBRC starting fall 2013
Hyung-Jin Kim	Kaon physics, $(g - 2)_\mu$, GPUs, . . .	BNL
Christoph Lehner	Kaon physics, B physics, CAS, . . .	BNL / RBRC
Tatsuhiro Misumi	New lattice fermions, Hosotani mechanism, . . .	BNL
Shigemi Ohta	Nucleon axial charge, Nucleon structure functions, . . .	RBRC
Sergey Syritsyn	Nucleon structure function, . . .	RBRC starting fall 2013
Eigo Shintani	Nucleon electric dipole moments, α_s , . . .	RBRC
Amarjit Soni	Kaon physics, B physics, . . .	BNL
Brian Tiburzi	QCD + QED, Hadron polarizability, . . .	RBRC / CCNY
Shinsuke Yoshida	Besides pQCD: Nucleon structure functions?, . . .	Tsukuba

. . . and many close collaborators at Columbia, UConn, and BU; collaborations with UKQCD and JLQCD



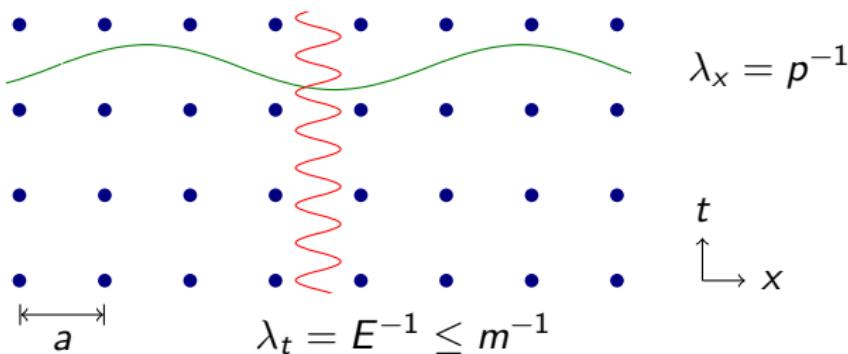
$\Delta M_s / \Delta M_d$ green
 $\sin 2\beta$ yellow
 $|V_{ub}/V_{cb}|$ (avg) red
 $\epsilon_K + |V_{cb}|$ blue



$\Delta M_s / \Delta M_d$ (No error in ξ)
 $\sin 2\beta$
 $|V_{ub}/V_{cb}|$ (avg)
 $\varepsilon_K + |V_{cb}|$

Simulation of heavy quarks on the lattice

- ▶ Problem: Heavy mesons “fall through the lattice”



- ▶ Mesons with mass m , momentum p , and energy $E=\sqrt{m^2+p^2}$
- ▶ Typical scales:
 $a^{-1} \approx 2 \text{ GeV}$, $m_D \approx 2 \text{ GeV}$, $m_B \approx 5 \text{ GeV} \Rightarrow am \geq 1$;
 $m_\pi \approx 0.2 \text{ GeV}$, $L = 32a \Rightarrow m_\pi L \approx 3$

Relativistic heavy quarks

(El-Khadra et al. 1997)
(S. Aoki et al. 2003) (Christ et al. 2006)

- ▶ Columbia formulation:

$$S = \sum_x \bar{Q}(x) \left((\gamma_0 D_0 - \frac{1}{2} D_0^2) + \zeta \sum_{i=1}^3 (\gamma_i D_i - \frac{1}{2} D_i^2) + m_0 + c_P \sum_{\mu, \nu=0}^3 \frac{i}{4} \sigma_{\mu\nu} F_{\mu\nu}(x) \right) Q(x)$$

- ▶ Tune coefficients of dimension 4 and 5 operators to remove $|a\vec{p}|$, $(am)^n$, $|a\vec{p}|(am)^n$ errors in on-shell quantities:

$$m_0, \zeta, c_P$$

- ▶ Matching of on-shell matrix elements of, e.g., HL operators requires $Q'(x) = Q(x) + d_1 \sum_{i=1,2,3} \gamma_i D_i Q(x)$ with parameter d_1 .

- ▶ Since d_1 only enters through the field rotation, it has no effect on the hadron spectrum of the theory.
- ▶ We can tune m_0 , ζ , and c_P non-perturbatively using meson masses and make predictions about the mass spectrum without knowledge of d_1 :

- ▶ $\bar{m} = (m_{B_s} + 3m_{B_s^*})/4 \stackrel{!}{=} 5403.1(1.1) \text{ MeV}$

- ▶ $\Delta_m = m_{B_s^*} - m_{B_s} \stackrel{!}{=} 49.0(1.5) \text{ MeV}$

- ▶ $E = m_1 + \frac{p^2}{2m_2} + \mathcal{O}(p^4); m_1 = m_2$

Only HL quantities

For (axial-)vector operators or four-quark operators we need Lattice PT to determine higher-dimensional correction terms.

- ▶ Wrote from scratch new computer algebra system (CAS) as a C++ library
- ▶ Direct access to parsed expression tree in C++
- ▶ Speed comparable to FORM, for some applications faster
- ▶ Some special features: function map, optimized series expansion, hooks

On top of new CAS: unified LPT, continuum PT framework

Excerpt of RHQ tuning code

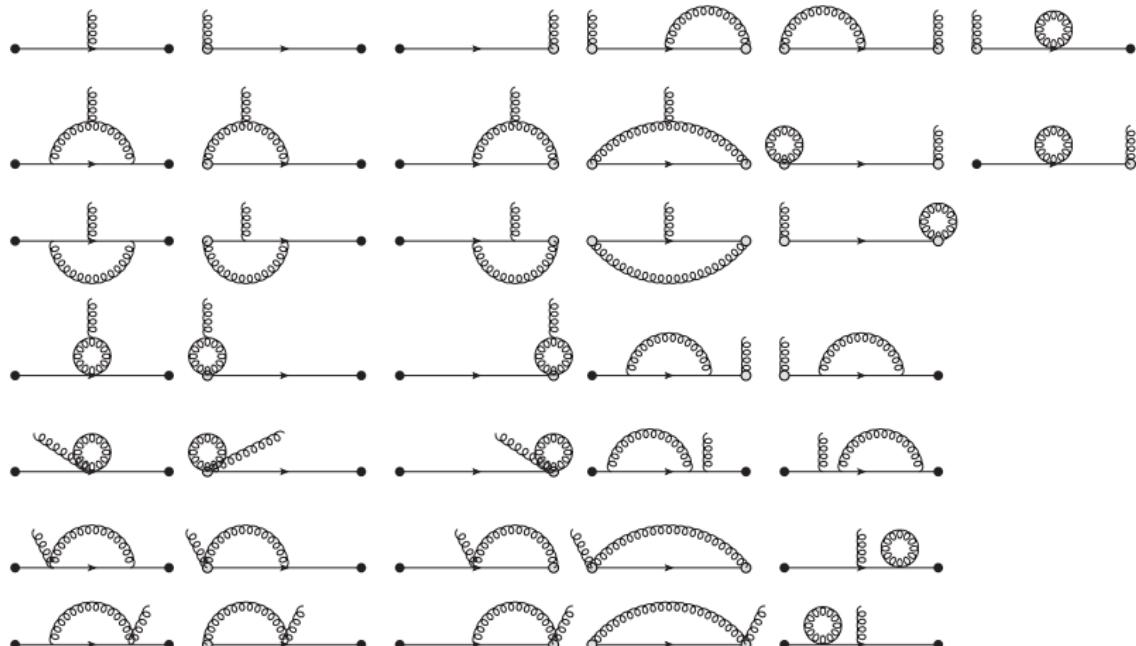
```
Context c;

// use rhq + gauge action
ActionRHQ rhq(&c, "Q");
ActionGAUGE gauge(&c);

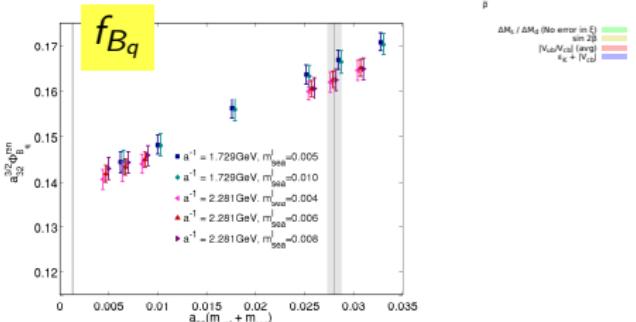
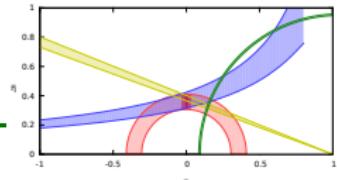
// define field rotations
c.coefficients << "d1FT";
FieldRotationRHQ Qimp(&c, "Q", "QimpmomT",
    "(1 + sum(i,4)*d1FT(i)*Ngamma(i)*aD(i,x))*Q(x)");
FieldRotationRHQ Qbimp(&c, "Qb", "QbimpmomT",
    "Qb(x)*(1 - sum(j,4)*d1FT(j)*Ngamma(j)*aDl(j,x))");

// perform wick contractions
Wick w(&c);
w << rhq << gauge << Qimp << Qbimp;
Expression* vertex = w.contract(
    "sum(k,mom)*QimpmomT(q)*aACmom(mu1,a1,k)*QbimpmomT(-p)", 3);
Expression* prop = w.contract(
    "sum(q,mom)*QimpmomT(p)*QbimpmomT(q)", 2);
```

One loop vertex graphs



Conclusion and Outlook



- ▶ Currently finalizing
 - ▶ f_B, f_{B_s} (Witzel)
 - ▶ $B \rightarrow \pi l \nu$ (Kawanai)
 - ▶ $g_{B^* B \pi}$ (Flynn, Samways)
- ▶ Preparing for $B - \bar{B}$ mixing and $\xi = f_{B_s} \sqrt{B_{B_s}} / f_{B_d} \sqrt{B_{B_d}}$
- ▶ Outlook (reduction of error): two-loop matching, tuning of highly-improved actions
- ▶ CAS/LPT applied to SF, Gradient Flow (CL, A. Shindler)